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ELECTROACOUSTIC PROJECTOR DESIGN GUIDELINES FOR HIGH SOURCE LEVEL, LONG DUTY CYCLE APPLICATIONS

Louis H. Fowler

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Final Report Under Contract N00014-70-A-0166, Task 0011

1 April 1972 - 31 March 1973

OFFICE OF NAVAL RESEARCH
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Louis H. Fowler

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ABSTRACT

In an effort toward the development of guidelines for consideration of thermal properties of ceramic in the design of electroacoustic projectors, a mathematical model for predicting changes in ceramic temperature of projectors operating at high power levels was developed and tested. The change in ceramic temperature as a function of heat dissipated in the ceramic was measured for two projectors under various operating conditions at ARL's Lake Travis Test Station. A determination of the unknown constant of proportionality γ was made on the basis of the data obtained. The average value $\langle\gamma\rangle$ should be useful in estimating temperature rise in a sonar array similarly constructed, using Channelite 5400 ceramic elements. The extent this value of $\langle\gamma\rangle$ can be extrapolated is unknown at present. (U)

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I. INTRODUCTION

This report summarizes the work performed under Contract N00014-70-A-0166, Task 0011, which is a continuation of Contract N00014-70-A-0166, Task 0001, Item 9, Exhibit I, Sonar Array Studies. The major endeavor under these contracts has been the development of design guidelines for sonar projecting arrays to be used for high source level, wide sector applications.

The first year's effort, detailed in Ref. 1, began with a literature survey concerning general power limits of sonar transducers and piezoelectric properties of various ceramics used in projector construction. Equivalent circuit techniques used in designing sonar projectors, and examples of the application of such techniques, were reviewed in the literature. The piezoelectric equations of state, including dielectric and elastic losses, were developed, and the effects of high drive levels and temperature changes on ceramic characteristics were predicted for several ceramics assuming no heat losses.

Coincident with the work on ceramic characteristics and equivalent circuit analysis, a computer study was made concerning the dependency of array beamwidth and directivity index on such factors as array configuration, element size and type, and amplitude shading. This study included a determination of the relationship between directivity, source level, and acoustic power of curved face arrays.

At the beginning of the present contract year, the major effort involved the development of a mathematical model for predicting the changes in ceramic temperature which occur in projectors operating at high power levels. Initial efforts to develop a detailed model for this purpose were terminated because of the unwieldly complexity of the mathematical development. A second model based on a lumped parameter approach was subsequently used.

To ascertain the validity of the temperature model, it was necessary to conduct experiments designed to acquire temperature data on test arrays operating under conditions simulating those encountered by operating sonar systems. To this end, the equipment necessary for collecting these temperature data was assembled at ARL's Lake Travis Test Station (LTTS). Experimental projecting arrays were designed and constructed from surplus materials available at ARL, and experimental data were collected. The final effort of this contract year has been concerned with analyzing and interpreting the experimental data.

The remainder of this report is divided into five sections. Section II discusses the array temperature prediction model. The equipment and test procedures are discussed in Section III. The experimental data are presented in Section IV, the data analysis in Section V, and conclusions and recommendations in Section VI.

II. MATHEMATICAL MODEL OF THE THERMAL PROPERTIES OF TRANSDUCER ARRAYS

One of the more common designs employed in sonar transducer construction may be described as a "sandwich" construction. The various layers of the sandwich include a metal support frame, a pressure release corprene layer, the ceramic motor, and an acoustical window (Scotchcast) separating the ceramic layer from the water medium. The initial attempt at deriving a mathematical model of the thermal properties of a transducer involved the solution of the one-dimensional heat flow equations with boundary conditions appropriate to the above specified layered media. To simulate heat dissipation in a pulsed sonar, the ceramic layer was treated as a periodic volumetric heat source.

As work on solving the thermal boundary value problem progressed, it became apparent that the equations were intractable. Further efforts to obtain a rigorous solution to the instantaneous heat flow models were believed unwarranted. Thus, a second approach to the problem was considered. For this approach, it was assumed that the thermal properties of the transducer array could be modeled on the basis of the average rate of heat flow through the system and the average heat within the system. Figure 1 is a diagram of this simplified curved face model.

If P_E, P_A, and P_H represent the average electrical input power, average acoustical output power, and average power dissipated as heat, respectively, then for well designed projectors (low mounting losses)

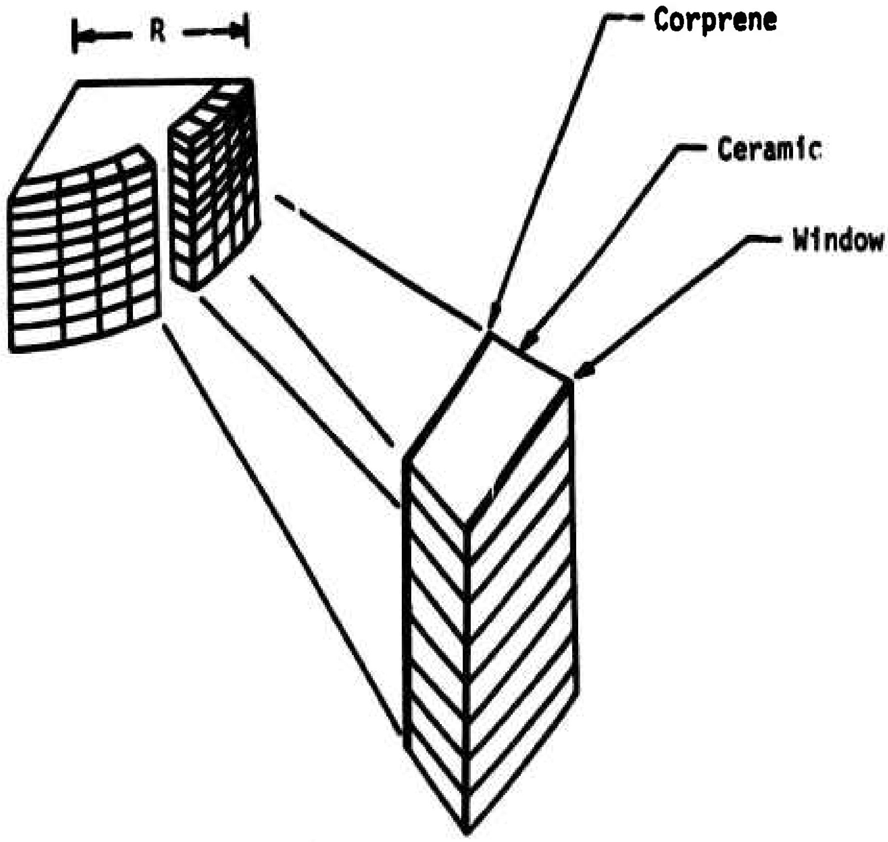

FIGURE 1

DIAGRAM OF SIMPLIFIED PROJECTOR
FOR "AVERAGE POWER" HEAT FLOW MODEL

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$$P_E \cong P_A + P_H \quad .$$

If Q_R represents the rate of heat loss from the ceramic, then

$$P_H - Q_R = M_c Q_c \frac{dT}{dt} \quad ,$$

where

M_c = ceramic mass,

Q_c = ceramic thermal capacity, and

T = temperature.

The rate of heat loss, Q_R, is proportional to the temperature differential between the ceramic and water,

$$Q_R = \gamma (T_c - T_w) \quad ,$$

where

γ is the constant of proportionality (the heat dissipated per unit area of ceramic to effect a 1°F change in temperature), and T_c and T_w are the ceramic and water temperatures, respectively.

The equations for the transient and the steady state temperature in the ceramic are then

$$T_c = T_{oc} + \frac{P_H}{\gamma}\left[1 - \exp\left(-\frac{\gamma t}{M_c Q_c}\right)\right] \quad , \text{ Transient Solution} \quad ,$$

and

$$T_c = T_{oc} + \frac{P_H}{\gamma} \quad , \text{ Steady State Solution} \quad ,$$

where

T_{oc} is the initial ceramic temperature (assumed equal to the water temperature T_w).

Based on the one-dimensional thermal model, the unknown constant γ is proportional to the frontal surface area of ceramic. A determination of the value of γ from first principles for a specific array requires a knowledge of the thermal contact resistances at the various interfaces within the array. The most appropriate method for determining γ for a specific array was to experimentally determine the quantities T_c, T_{oc}, and P_H for the test arrays under consideration. A description of the apparatus used for this purpose is given in the next section.

III. TEST APPARATUS

A schematic diagram of the test apparatus used in these experiments is shown in Fig. 2. Use of the external oscillator and pulser in conjunction with the AN/UQS-1B transmitter enabled the test stave to be driven at various repetition rates and variable pulse lengths over the frequency range from approximately 99 kHz to 102 kHz. The bandwidth limitations resulted from the highly tuned power output stages in the AN/UQS-1B transmitter (the transmitter was manufactured to deliver 10 kW of peak pulse power in a 1 msec pulse at 100 kHz).

Two test projectors were constructed for use in the ceramic heating experiments. One projector, designated 0166-11-1, was a linear array of thirteen identical Channelite 5400 elements. The dimensions of the acoustic radiating surface of the elements used in this array were 0.187 in. x 0.46 in.; the applied field dimension was 0.625 in. Each element was isolated from adjacent elements by a 0.03 in. layer of corprene. The total radiating dimensions of the array were 2.8 in. x 0.46 in. Two Fenwal Type BG41J1 thermistors mounted on each array, one on the front surface and one on the rear surface of the center ceramic element, were used to monitor the ceramic temperature during pulsing.

The second projector, designated projector 0166-11-2, was constructed similar to projector 1, except that it consisted of eight Channelite 5400 elements of dimensions 0.41 in. x 0.355 in. x 0.53 in. The elements and corprene spacing form a radiating surface of 3.49 in. x 0.355 in. The two arrays have different facial areas. The particular facial area of each projector used was determined by the size of the surplus ceramic elements available and the number of them selected for each array.

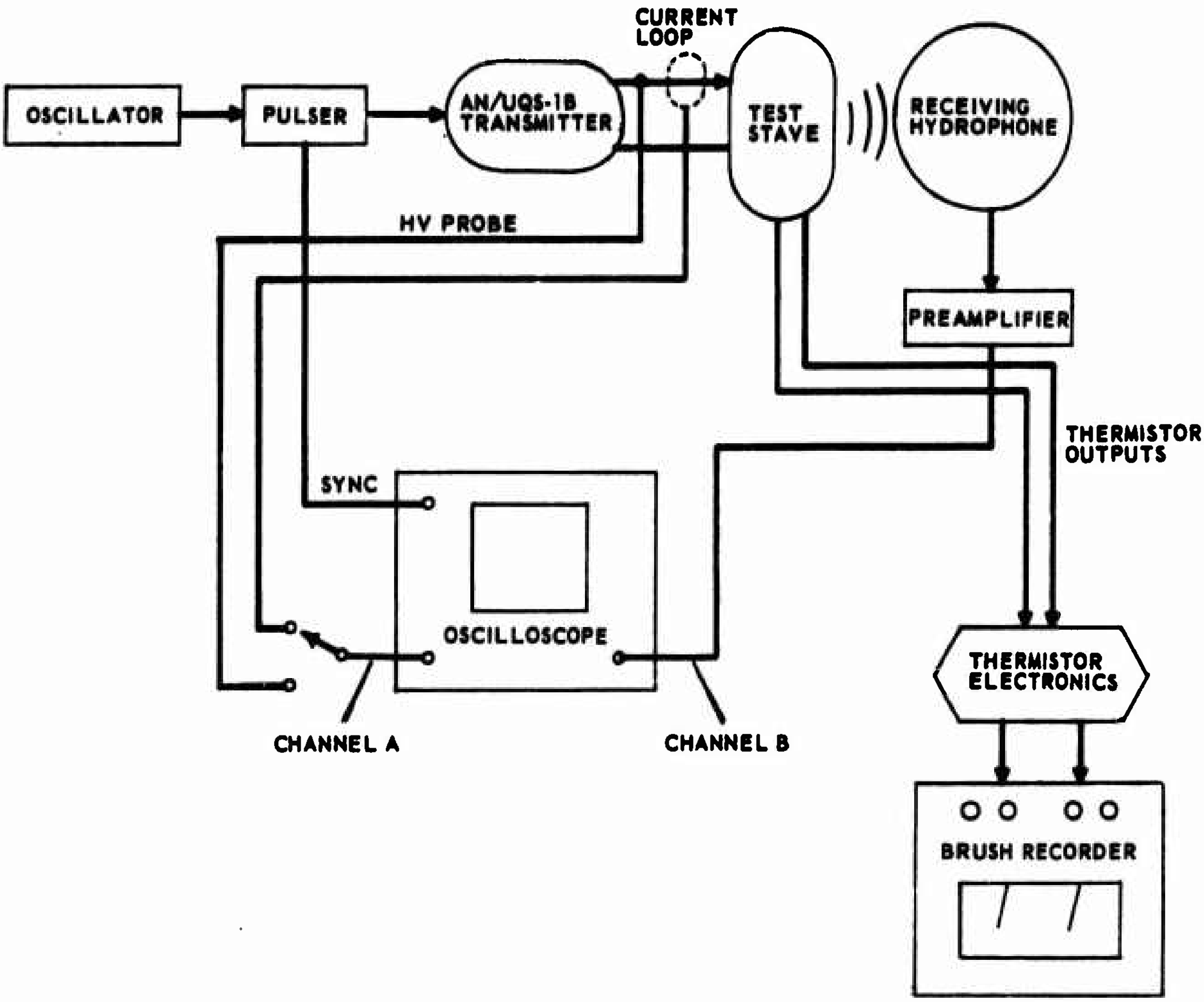

FIGURE 2
BLOCK DIAGRAM OF TEST APPARATUS

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The projector and hydrophone in these experiments, conducted at the LTTS, were operated in water at a depth of 10 ft. The hydrophone (an in-house variety) was omnidirectional (±0.5 dB) in the horizontal plane with a 40° vertical beamwidth. The projector acoustic axis was aligned with the hydrophone to produce the maximum acoustic signal.

IV. DATA ACQUISITION

A. Measurement of Projector Low Level Impedance as a Function of Temperature

To better understand the effects of temperature on the performance of a transducer, measurements were made of the input impedances of projectors 1 and 2 as functions of temperature. The impedance components were determined using a General Radio impedance bridge with each projector immersed in a Mason Tank. The water temperature was artificially controlled to obtain the various temperatures. The Mason Tank construction (sound absorbing walls), coupled with the low efficiency of the projectors, appeared to provide conditions approaching freefield. No changes in impedance components, either resistive or reactive, could be detected when either of the projectors was moved with respect to the tank walls.

The measured low level input resistance and reactance for projector 1 (cable effects included) are shown for four ceramic temperatures in Figs. 3 and 4, respectively. Similar curves for projector 2 are given in Figs. 5 and 6. The data contained in Figs. 3 and 5 are summarized in Fig. 7, where the percentage change in the input resistance of each projector measured at two temperatures is plotted as a function of frequency. The percentage change in the input resistance resulting from a change in temperature is given at a particular frequency by

$$\Delta R(T_1,T_2) = \frac{R(T_2) - R(T_1)}{R(T_1)} \times 100 \quad ,$$

where

$R(T_1)$ = measured input resistance at temperature T_1, and

$R(T_2)$ = measured input resistance at temperature T_2.

For projector 1, T_1 = 70°F and T_2 = 153°F. For projector 2, T_1 = 77°F

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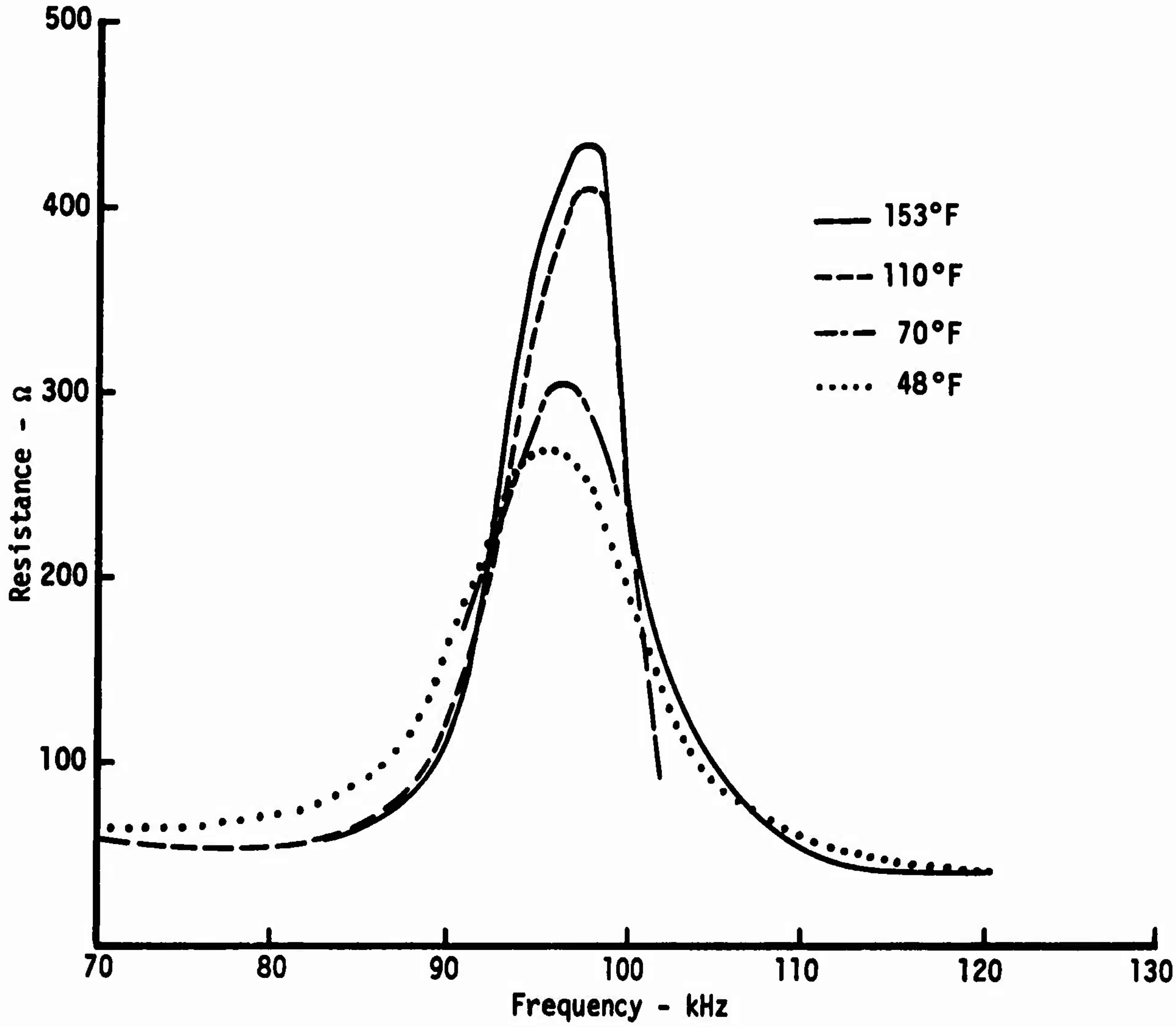

FIGURE 3

MEASURED LOW LEVEL INPUT RESISTANCE
OF PROJECTOR 0166-11-1 AT FOUR TEMPERATURES

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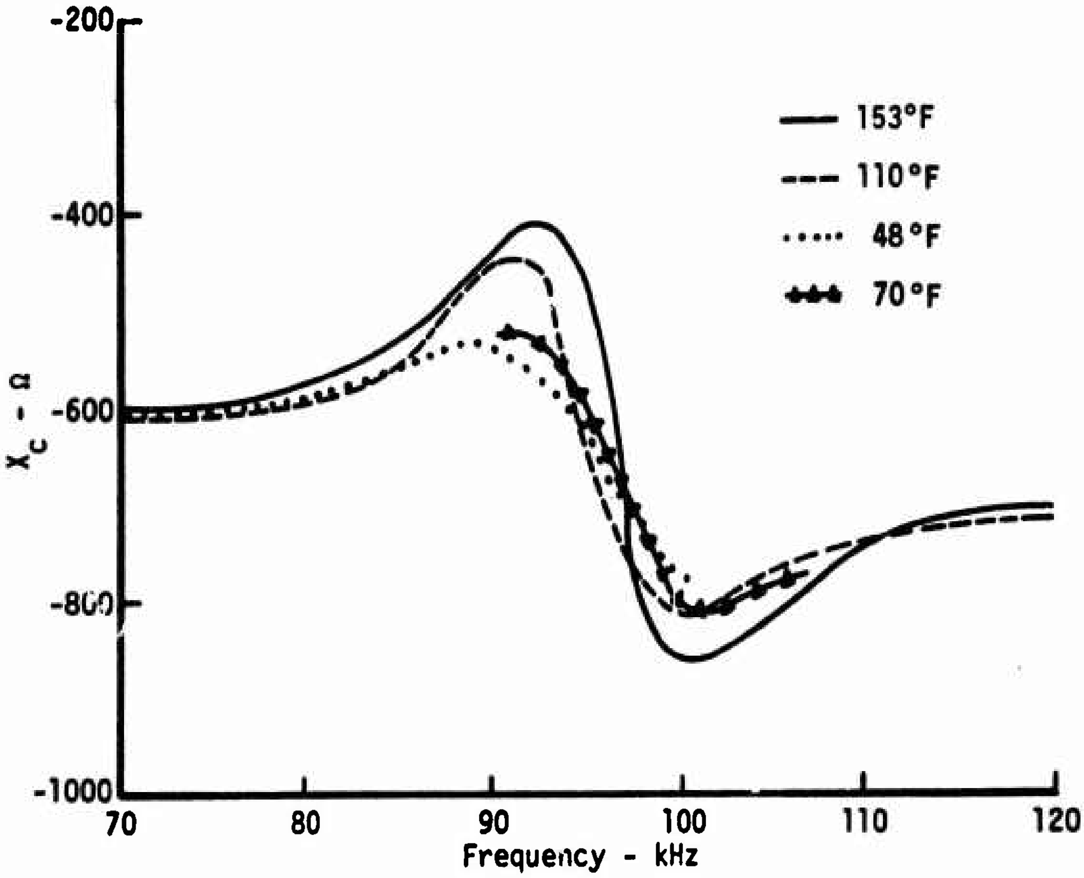

FIGURE 4

MEASURED LOW LEVEL INPUT REACTANCE
OF PROJECTOR 0166-11-1 AT FOUR TEMPERATURES

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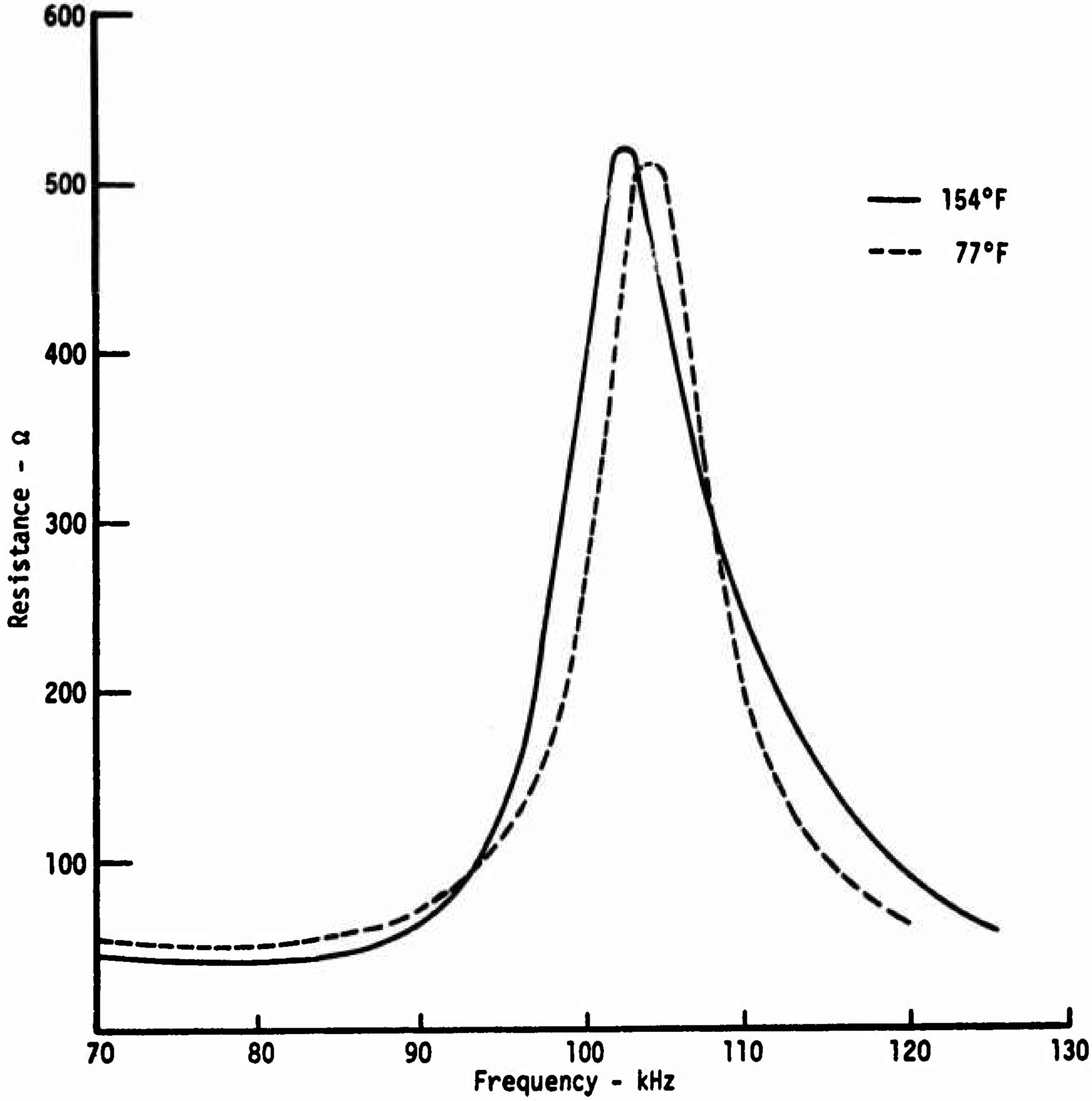

FIGURE 5

MEASURED LOW LEVEL INPUT RESISTANCE
OF PROJECTOR 0166-11-2 AT TWO TEMPERATURES

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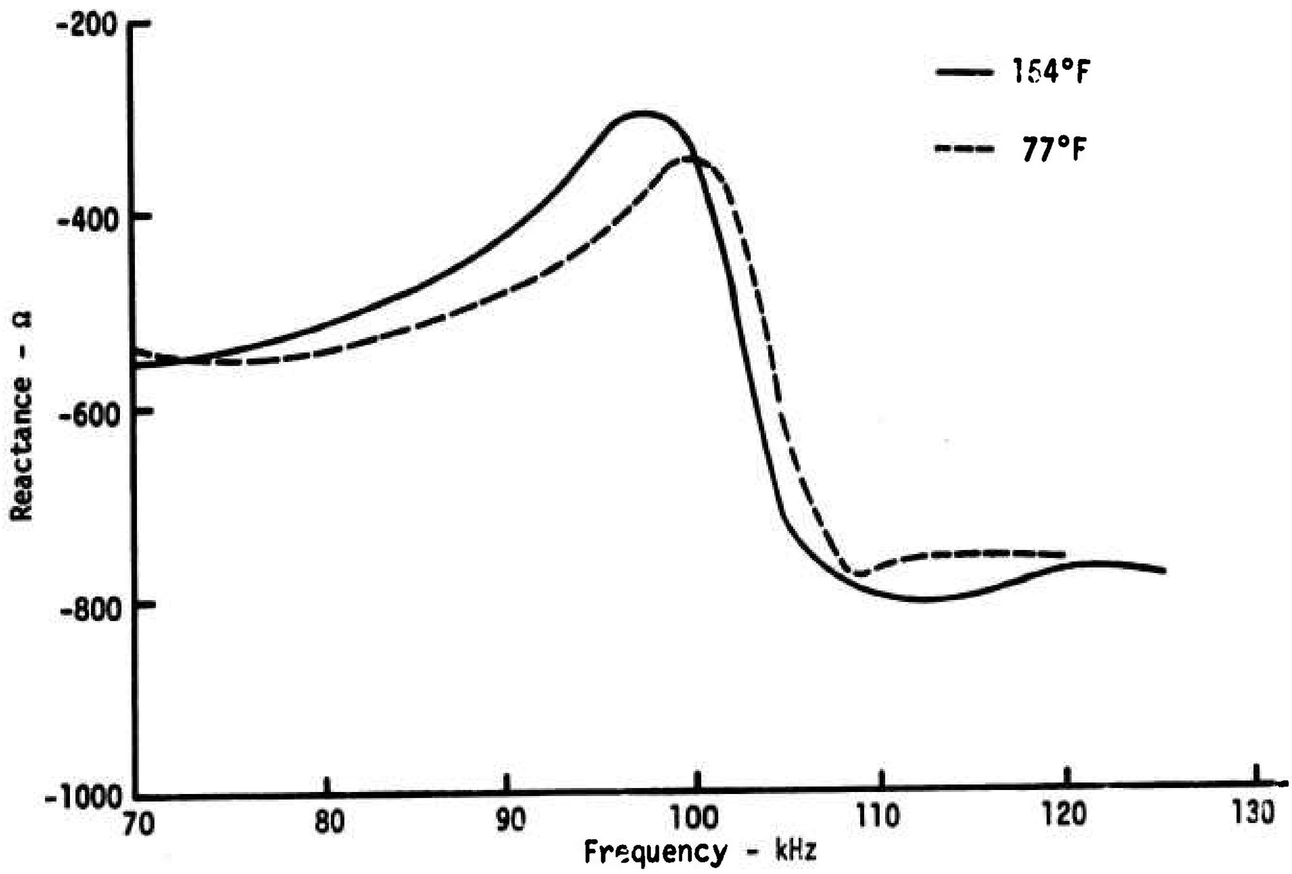

FIGURE 6

MEASURED LOW LEVEL INPUT REACTANCE
OF PROJECTOR 0166-11-2 AT
TEMPERATURES OF 77°F AND 154°F

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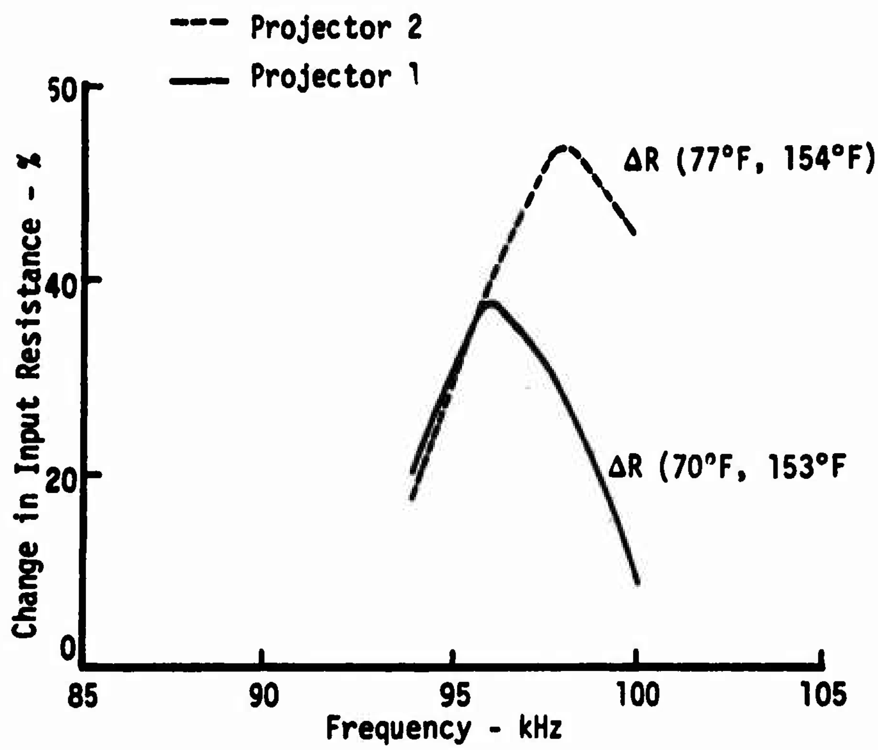

FIGURE 7

CHANGE IN MEASURED LOW LEVEL INPUT RESISTANCE
OF PROJECTOR 0166-11-1 AND PROJECTOR 0166-11-2

AS-73-1406

and T_2 = 154°F. The temperature effects, as seen in these examples, are not negligible. Figure 7 shows that the measured input resistance of projector 2 changed by as much as 54% at 96 kHz over the temperature range from 77°F to 154°F.

A second example of the effects of temperature change on the low level impedance is given in Table I where the low level power factor of projector 1 at 101 kHz is given for four temperatures. It is seen from these data that the power factor of projector 1 changes by as much as 25% at this frequency.

Any changes in the measured impedance components between two temperatures at a particular frequency must be attributed to a combination of two effects: 1) the change in the acoustic load with changing temperature, and 2) the change in ceramic characteristics with temperature (cable effects are constant in the measurements and, therefore, contribute nothing to impedance change as a function of temperature). The differences in temperature dependence exhibited by these two projectors are probably a function of ceramic element size differences and ceramic parameter variation between different batches of the same ceramic. It was impossible to further investigate the causes of such differences, within the budgetary limits of this contract.

B. Array Temperature Data

Temperature data were obtained on projector 1 operating untuned at approximately 101.6 kHz and on projectors 1 and 2 operating tuned (series inductance) at 100 kHz. Each temperature run lasted ten minutes and began with the array in thermal equilibrium with the water. The array temperature had stabilized by the end of the ten minute interval for each drive condition tested.

TABLE I

LOW LEVEL POWER FACTORS OF PROJECTOR 1 AT 101 kHz
CALCULATED FROM IMPEDANCE MEASUREMENTS AT FOUR TEMPERATURES

Temperature (°F)	$\cos\theta = \frac{R}{\lvert Z \rvert}$
48	0.212
71	0.221
110	0.179
158	0.223

The arrays were driven by a 1 msec electrical pulse generated by the AN/UQS-1B transmitter. The electrical input power was controlled by adjusting either the duty cycle, the drive level, or both. To verify that the projectors were not being driven into a nonlinear operating region, the SPL determined from the projector calibration was compared with that determined from the hydrophone measurements. The comparison can be seen from Fig. 8. The calibration curves for both tuned projectors are shown along with the data points for the SPL's, determined from the hydrophone data, at the highest drive levels attainable with the AN/UQS-1B transmitter.

The pertinent results from the experimental data obtained on the two test arrays are presented in Fig. 9. The change in ceramic temperature (T_{FINAL} - $T_{INITIAL}$) is plotted as a function of the power dissipated as heat in the array per unit ceramic facial area for the cases shown. The data presented are applicable to the highest power levels attainable with AN/UQS-1B equipment.

As observed in Fig. 9, a discrepancy is apparent for the temperature versus power curve for tuned projector 1. Although good agreement exists between the three curves at the lower power levels, the tuned projector 1 curve deviated at the higher drive levels. A check of the measured SPL's for these runs indicated ceramic linearity was maintained during the runs. Calculations of the input power for these runs, based on $e_d i \cos \theta$ and $i^2 R_{IN}$, agree with a worst case error of only 10%. (R_{IN} is the array input resistance; $\cos \theta$ is the array power factor; e_d is measured directly across the ceramic array.) Subsequent examination revealed a carbon build-up on the front face of the ceramic element on which the thermistor was mounted. From all appearances it is believed that the thermistor in projector 1 failed due to electrical insulation breakdown, and that this resulted in the recorded temperature discrepancy observed in Fig. 9.

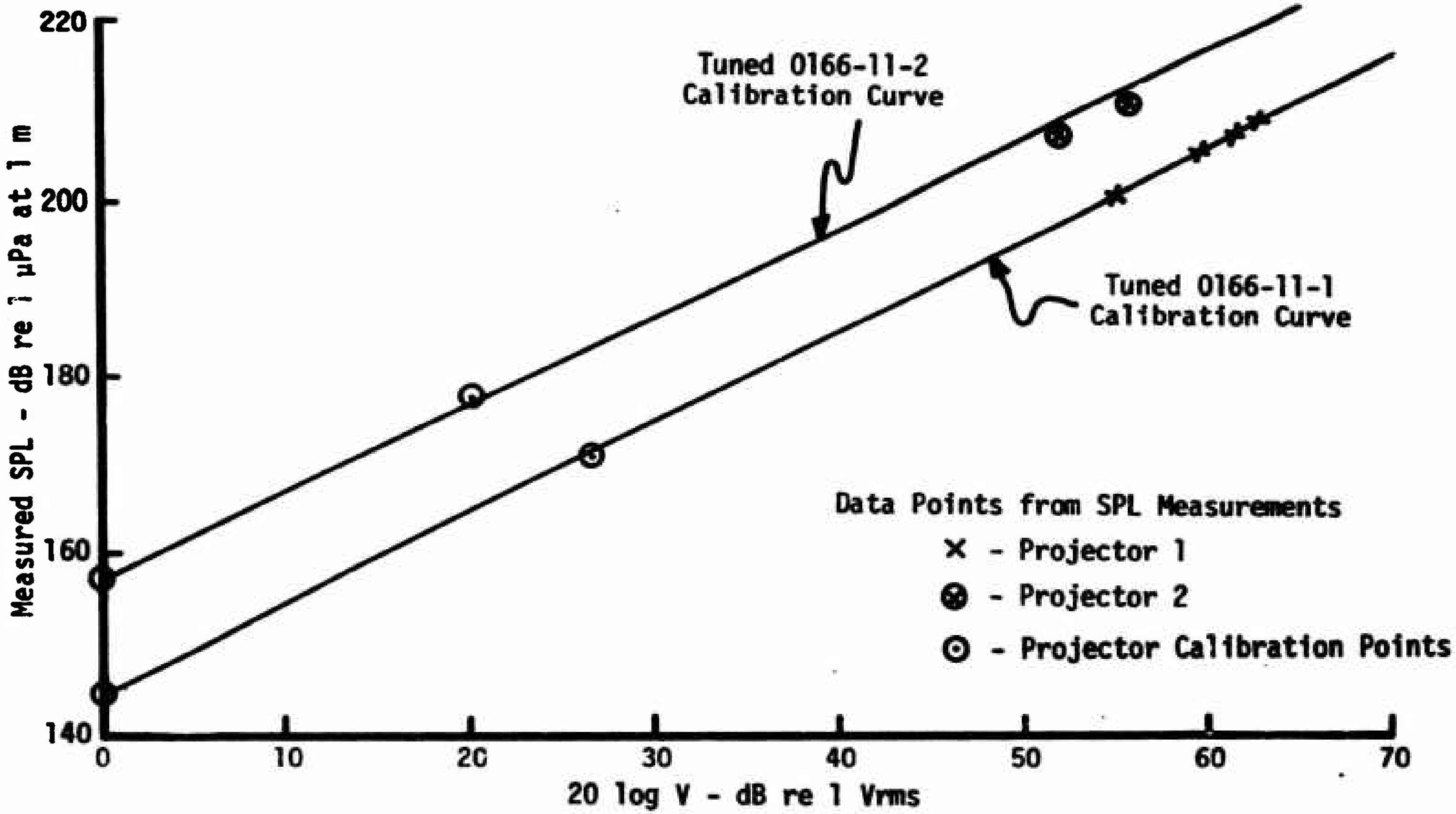

FIGURE 8

MEASURED SPL vs PROJECTOR VOLTAGE (dB) FOR TUNED PROJECTORS 1 AND 2

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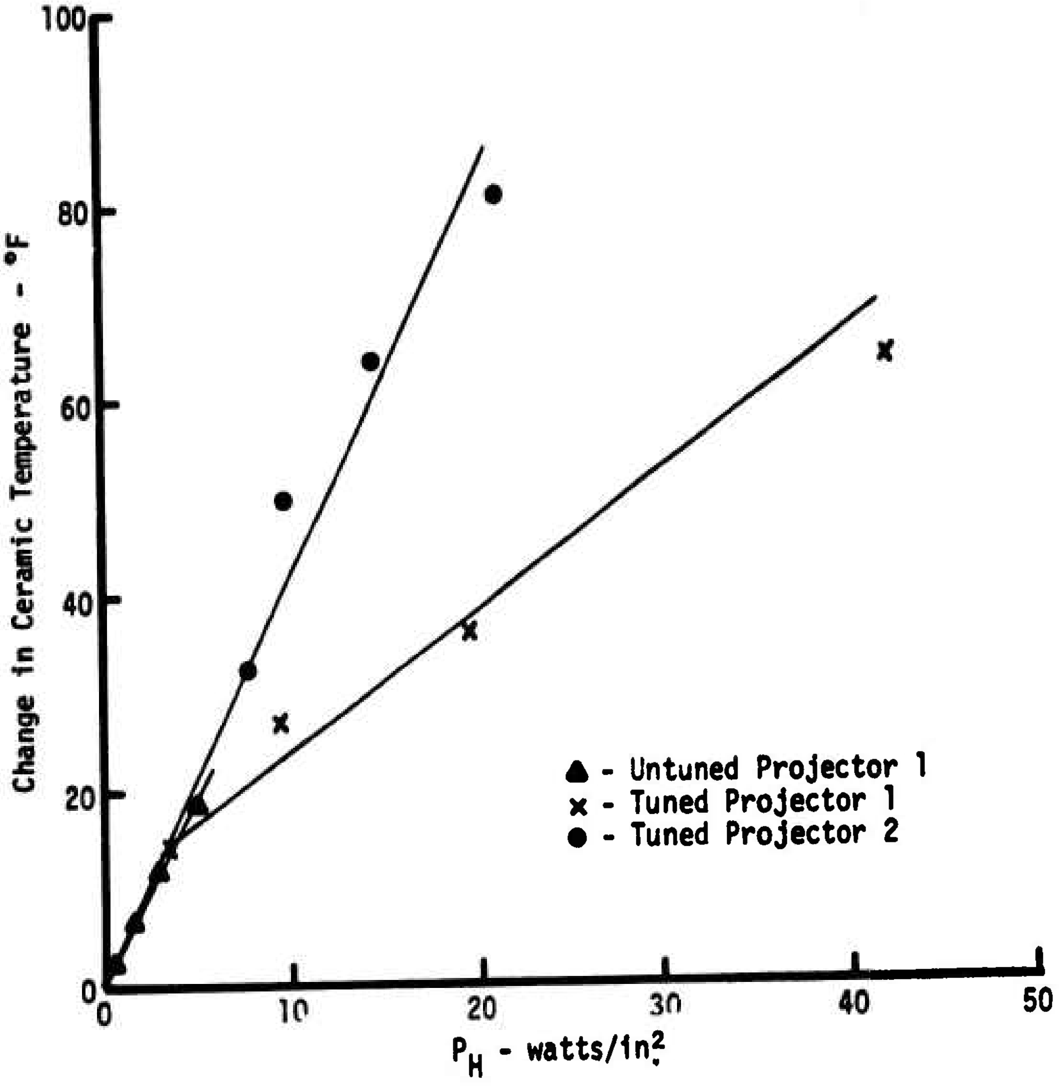

FIGURE 9

EQUIVALENT cw POWER DISSIPATED
IN CERAMIC AS HEAT

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V. DATA ANALYSIS

From the standpoint of heat generation, an equivalent cw power may be defined as pulse power times duty cycle. The equivalent cw power, $\langle P_H \rangle$, generated as heat in an array is given by

$$\langle P_H \rangle = \langle P_{IN} \rangle - \langle P_{OUT} \rangle$$

where

$\langle P_{IN} \rangle$ is the equivalent cw electrical power in, and
$\langle P_{OUT} \rangle$ is the equivalent cw acoustic power out.

For projector 1 (untuned),

$$\langle P_{IN} \rangle = e_d i \cos \theta \times \text{duty cycle} \quad ,$$

where $\cos \theta$ is the power factor determined from the bridge measurements. The value of $\cos \theta$ is assumed constant at the voltage levels encountered during these runs. For projector 1 (tuned), the value of $\langle P_{IN} \rangle$ was obtained from

$$\langle P_{IN} \rangle = i^2 R_{IN} \times \text{duty cycle}$$

and checked against

$$\langle P_{IN} \rangle = e_d i \cos \theta \times \text{duty cycle} \quad ,$$

where e_d is the voltage directly across the array. The quantity R_{IN} is the real impedance of projector 1 at the operating frequency of 100 kHz. (From Fig. 3, it is seen that R_{IN} is fairly temperature stable at 100 kHz.) The two calculations of $\langle P_{IN} \rangle$ for tuned projector 1 agreed with a worst case error of only 10%. The value of $\langle P_{IN} \rangle$ for projector 2 (tuned) was determined from

$$\langle P_{IN} \rangle \; e_d i \times \text{duty cycle} \quad ,$$

where e is the rms voltage across the tuning coil and transducer in series. The coil was assumed lossless, and the value of cos θ for the tuned projector was assumed unity.

The output power for each array for each run was calculated from

$$\langle P_{OUT} \rangle = \text{alog}_{10} \frac{\text{SPL} - \text{DI} - 171.6}{10} \times \text{duty cycle}$$

where SPL is the measured sound pressure level (referred to one yard) for the run, and DI is the projector directivity index. The value of DI for each projector was calculated from

$$\text{DI} = 10 \log_{10} \frac{4\pi \times \text{Area}}{\lambda^2} \quad .$$

This equation is applicable to a rectangular piston so long as the minimum dimension is greater than $\lambda/2$ and the length/width ratio is greater than 2 (Ref. 2). For projector 1, the DI was calculated to be 15.5 dB; for projector 2, the DI is 15.9 dB.

From the experimental data collected on these two test arrays, an average value $\langle \gamma \rangle$ for γ was calculated to be

$$\langle \gamma \rangle = 0.25 \frac{\text{watts}}{{}^\circ\text{F} - \text{sq in.}} \quad .$$

Thus for an array constructed similar to the test arrays, operating into a water load (thermal heat sink), 0.25 W dissipated as heat per square inch of ceramic cross sectional area would produce a temperature increase of 1°F.

On the basis of the results obtained, a hypothetical example is presented to illustrate design procedure. Assume an array (composed of Channelite 5400 elements) is to be operated at 100 kHz, and the required sector coverages are 10° (vertical) by 120° (horizontal). The necessary source level is assumed to be 230 dB re 1 µPa at 1 m.

For a vertical sector of 10° beamwidth, and using the expression for a uniform line (small spacing between elements), the vertical dimension can be shown to be approximately 4 in. for a 100 kHz array.

The horizontal sector coverage of 120° may be obtained using an angular width of about 140° (Ref. 1). The directivity index for such an array may be obtained by calculating

$$DI = 10 \log_{10} \frac{1}{W(z) \times \alpha} ,$$

where

α = half-power angular beamwidth (in radians), and

z = vertical height of a stave (in inches) $\times$ frequency (in kHz).

The function $W(z)$ is given as a function of z in Ref. 1. From the values of α and z assumed for the hypothetical array, a directivity index of 18.4 dB is obtained.

The output acoustical power P_o for a 230 dB re 1 µPa at 1 m source level is given by

$$10 \log_{10} P_o = 230 - 18.4 - 171.6$$

$$= 40 \text{ dB re 1 W.}$$

Thus, P_o = 10,000 W. It is assumed that this is the equivalent cw acoustic power generated by the array. If the array operates with

an assumed efficiency of 50%, then the rate that heat is dissipated in the ceramic will also be 10,000 W.

Assume, for the moment, that a ceramic temperature change of 150°F is acceptable during the course of operation. The required thermal surface area for dissipating the heat generated in the array may be calculated from the equation

$$\text{Area} = \frac{\text{cw power into heat}}{\langle\gamma\rangle \times \Delta T} \quad .$$

For this example

$$\frac{10000}{0.25 \times 150} = 270 \text{ sq. in.}$$

Thus, a radius of curvature, R, for this array is obtained by the equation,

$$R \times \theta \times h = \text{area} \quad ,$$

where θ is the array angular width in radians and h is array height. Thus, for this illustrative example,

$$R = \frac{270}{140 \times \frac{2\pi}{360} \times 4} = 28 \text{ in.}$$

The preceding example was based on a hypothetical array capable of handling 20,000 W (cw) of electrical input power. It was tacitly assumed that the ceramic motor elements would be operating in a linear applied field displacement region at this power level.

An illustration of the application of the data obtained during these experiments to a pulsed system is presented in Fig. 10. The

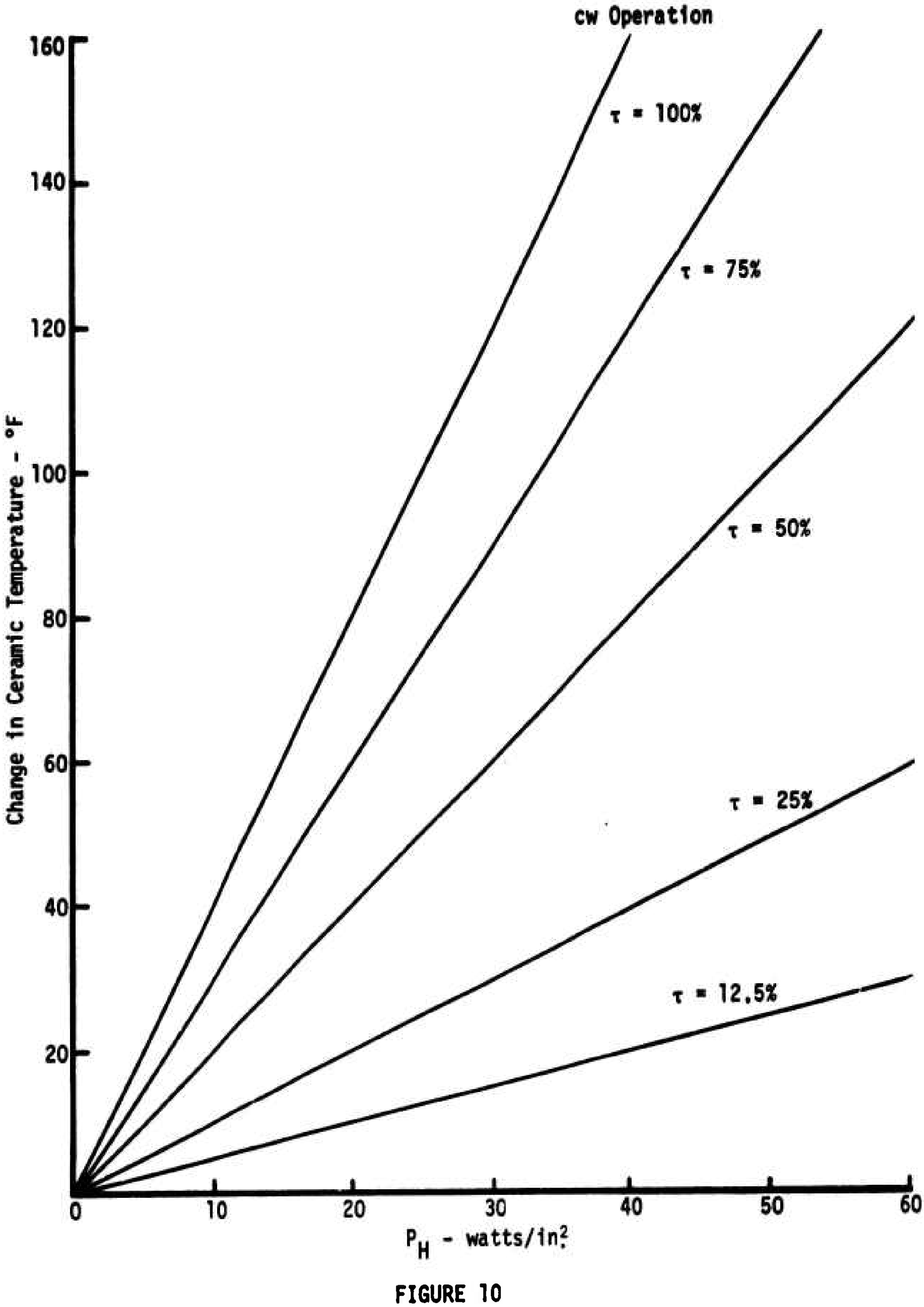

FIGURE 10

RELATIONSHIP BETWEEN PULSE POWER, DUTY CYCLE, AND EXPECTED TEMPERATURE CHANGE

change in ceramic temperature is plotted as a function of rms pulse power dissipated as heat per square inch of ceramic cross-sectional area for various duty cycles, τ. The limiting case of $\tau = 100\%$ is equivalent to a cw mode of operation. It should be remembered that nonlinear ceramic operation must be avoided.

VII. CONCLUSIONS AND RECOMMENDATIONS

The change in ceramic temperature as a function of heat dissipated in the ceramic has been measured for the arrays described. A determination of the unknown constant $\langle\gamma\rangle$ was made on the basis of the data obtained. The variation of ceramic characteristics known to exist from batch to batch requires that the value of $\langle\gamma\rangle$ determined in these experiments be accepted as an average value for this ceramic. It must be remembered that it is also based on a very limited set of data. It should be useful to provide an estimate of the expected temperature rise of an array similarly constructed from elements of the same type ceramic and operated under similar conditions. How far this value of $\langle\gamma\rangle$ can be extrapolated is unknown at present. It is known intuitively that element internal temperatures will be higher than the external temperature measured. Temperature gradients within the ceramic elements have not been determined due to the mathematical difficulties involved.

The experimental value of $\langle\gamma\rangle$ presented here is also useful to predict temperature rise in arrays other than curved face arrays--such as pistons constructed from a matrix of elements--so long as the same basic construction techniques are used. Of course the same type ceramic must be used.

The available test equipment was unable to supply sufficient power to heat the ceramic elements to failure. It is true that both arrays eventually failed, but the failure resulted from a burnout associated with the silver conductive paint applied to the ceramic surface.

From the impedance versus temperature data presented in Section IV, the importance of operating a projector at a frequency of low temperature dependence can be seen. If a projector is tuned to operate

at a frequency where the ceramic is highly temperature sensitive, optimum projector performance should not be anticipated. Loss of tuning and a resulting decrease in output power can be expected.

Further research along the same lines as the reported work would be very useful. Support data for the experimental values determined would provide additional confidence in their validity. A repeat of the present experimental work using a harder MIL-SPEC ceramic such as PZT 8 should provide useful information.

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